ELSEVIER

Agricultural Systems 70 (2001) 623–640

AGRICULTURAL SYSTEMS

www.elsevier.com/locate/agsy

Regional land use analysis: the development of operational tools

J.J. Stoorvogel[a,*], J.M. Antle[b]

[a]*Laboratory of Soil Science and Geology, Wageningen University, Duivendaal 10, PO Box 37, 6700 AA Wageningen, The Netherlands*

[b]*Department of Agricultural Economics and Economics, Montana State University, Bozeman MT 59717, USA*

Accepted 30 March 2001

Abstract

Regional land use analysis plays a key role in the analysis of agricultural policies. However, few operational tools for regional land use analysis are available. Current developments in regional land use analysis are rather ad hoc. More generic methodologies are required to effectively answer questions by policy makers. The analysis may require methods to explore, project and predict agricultural land use. An all-encompassing methodology seems unrealistic. A toolbox for regional land use analysis is proposed. The tools (including, e.g. database management systems, GIS and economic models) can be linked in such a way that they can carry out the analysis required for the specific conditions of stakeholders. To facilitate linkages between the different tools, data standards need to be developed for both bio-physical as well as economic data. Discussions with stakeholders in an early phase of the analysis may set priorities and determine the selection of tools. Results of the analysis need to be presented in such a way that they are appealing to the stakeholders. Only then can they be transferred effectively. The general framework is illustrated with a methodology for regional land use analysis in terms of economic and environmental trade-offs. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Agricultural policy; Land use analysis; Toolbox

* Corresponding author.

E-mail address: jetse.stoorvogel@bodlan.beng.wag-ur.nl (J.J. Stoorvogel).

0308-521X/01/$ - see front matter © 2001 Elsevier Science Ltd. All rights reserved.

PII: S0308-521X(01)00062-2

1. Introduction

With an increasing pressure on land, it becomes ever more important for policy makers to monitor land use changes and, if necessary, to influence these changes according to their specific objectives through agricultural policies and other policy mechanisms. Likewise, increasing resource scarcity increases the urgency to understand the environmental consequences of agricultural technologies. Changes in policy and technology can either mitigate or aggravate land use conflicts, minimize adverse environmental effects and maintain or increase agricultural production. A key component in achieving more sustainable agricultural production systems is the capability to assess the impacts of changes in policy or technology on land use and on the economic and environmental consequences of farmers' related production decisions. In this paper, we build upon the concept of regional land use analysis, showing how it can be integrated into more general, multi-disciplinary, policy-oriented, forward-looking studies. A major question that we will pose is whether we have tools available that are operational and, if not, what is required to develop them?

Several methodologies have been developed in the past to project (e.g. CLUE by De Koning et al., 1999), explore (e.g. SysNet by Hoanh et al., 1998, SOLUS by Bouman et al., 1999), and predict (Trade-off model by Crissman et al., 1998) agricultural land use. However, the process of assessing prospective impacts of policies and technologies does not end with the projection of trends nor with the exploration of opportunities. To effectively develop, select and implement agricultural and other land use policies we need to project, explore and predict agricultural land use (Van Ittersum et al., 1998). An all-encompassing methodology seems unrealistic. Consequently, we need a range of methodologies that serve different purposes and that apply to different situations. Despite many commonalties, the available methodologies are based on very different procedures. Some apply linear programming techniques (e.g. SysNet and SOLUS), others are based on statistical techniques (e.g. CLUE), while others use simulation models (e.g. the Trade-off model). Current developments in regional land use analysis can be described as being rather ad hoc since many methodologies are developed for specific situations. As a result, they are not very generic. Basic concepts and procedures are available and each particular project dealing with regional land use analysis takes a number of techniques from the shelf and starts creating their own application.

The development of a user shell over different crop growth simulation models (Jones et al., 1998) together with the appropriate data standards (Hunt et al., 1994) has played a crucial role in the rapid developments in the field of land use analysis at the field level. To gear the development of tools for regional land use analysis, a similar thrust needs to be made in which the International Consortium for Agricultural Systems Applications (Ritchie, 1995) can play an important role. Standards for database formats need to be developed together with more generic versions of regional land use analysis tools. Are there opportunities? The requirements are certainly different and probably more diverse than data standards for crop growth simulation models. In this paper, we would like to explore the opportunities for the development of operational tools for regional land use analysis. First, we describe a

number of basic concepts, where after we discuss the implementation of regional land use analysis using a case study.

2. Basic concepts

2.1. Actors and stakeholders

It is impossible to study regional land use without considering the people and institutions that play a role in the region. The most successful land use studies are being carried out in close interaction with the people and institutions involved. In this paper, we distinguish between stakeholders and actors. The stakeholders are the parties directly interested in the outcomes of the study. They will be the future users of the results of the study or the methodology under development. Despite studies that are strictly scientific exercises, studies (e.g. in development projects) are (or should be) shaped around the objectives of the stakeholders. The actors, on the other hand, are all the people in the region that to some extent play a role in the agricultural sector. Farmers, for example, make land allocation and land management decisions and, as a result, play a key role in agricultural land use. They are, however, not the target group for the results and methodologies of regional land use studies and, consequently, they are referred to as actors and not as stakeholders. Many tools for regional land use analysis are developed to answer questions of regional or national policy significance and as a result policy decision makers, politicians, and the general public are the principal stakeholders of the study. When the analysis focuses on the impacts of technology adoption, research administrators and related interests should also be considered stakeholders.

2.2. Model objectives

Policy-oriented, regional land use studies are often sub-divided on the basis of their objectives into explorative, projective and predictive models (Van Ittersum et al., 1998).

Explorative studies determine what can be done where and when. Agricultural land use is restricted by numerous bio-physical and socio-economic constraints. The full set of opportunities, hereafter referred to as the opportunity space, includes the range of all possible options. In contrast, the decision space refers to the range and nature of the options considered by the stakeholder being relevant and potentially achievable (Lemon, 1999). Ideally, decision space and opportunity space coincide, but reality shows that the two spaces only partially overlap resulting in three sets of options by the partially overlapping opportunity space A and the decision space B (schematically represented in Fig. 1):

$A \cap B$: Options that are viable (within the opportunity space A) and that are considered to be relevant and potentially viable by the actor(s) (within the decision space B).

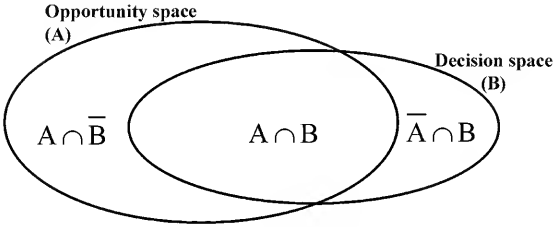

Fig. 1. Schematic representation of the overlapping opportunity space and decision space.

$A \cap \bar{B}$: Options that are viable (within the opportunity space A) but that are not considered to be relevant and potentially viable by the actor(s) (outside the decision space B). Extension can play a key role to create awareness with respect to these options and to include them in the decision space.

$\bar{A} \cap B$: Options that are considered to be relevant and potentially viable by the actor(s) (within the decision space B), but that are not viable (outside the opportunity space A). Also, extension can play a role here. Here, however, its function is to create awareness about the impact of certain options.

Explorative land use studies show the opportunity space to the stakeholders. It pinpoints to viable options the stakeholders are not aware of and to options considered relevant by the stakeholders that are, in reality, not viable. If the results of explorative land use studies are transferred successfully to the stakeholder, the decision space and the opportunity space will coincide.

Projective models study past land cover and land use changes in relation to biophysical and socio-economic parameters and project future trends given certain changes in the parameters. In other words, where does regional land use move within the opportunity space? Due to their inherent characteristics, projective models are generally unable to capture abrupt changes in agricultural land use caused by, for example, natural disasters, the collapse of markets, or the introduction of completely new agricultural technologies. Nevertheless, projective studies are important to policy makers because they indicate possible changes without policy interventions or as a result of technological changes. Policy makers can subsequently decide whether these trends are desired or not and whether intervention is justified.

Finally, predictive models have been developed that actually predict land use changes as a result of agricultural policies or technologies. Predictive land use studies answer scenario type 'What-If'-questions and indicate where agricultural land use will move within the opportunity space after implementing a certain agricultural policy. As such, predictive models simulate the compound human behavior and decision making of all agricultural households. Due to uncertainties in the prognoses of many drivers governing land use change, predictive models can only be applied with a short time horizon.

These three groups of models have a large complimentary value. Explorative models identify the possibilities in the opportunity space, projective models indicate what will happen to agricultural land use if trends continue, and the projective models characterize the likely impacts of changes in agricultural policy or technology.

2.3. Policy instruments

Stakeholders have an array of alternative policy instruments available that allow them to move agricultural land use within the opportunity space according to their specific objectives. A large number of policy instruments can be identified. Some examples from Lemon (1999), Van Keulen et al. (1998) and Wiebe and Meinzen-Dick (1998) are given below.

Macro-economic policies:

- Price liberalization.
- Removal of quantitative and administrative trade barriers.
- Redefining the role of the government.

Price policies:

- Subsidies on agricultural inputs and/or products.
- Price support that guaranties prices for agricultural products.

Regulatory instruments:

- Environmental regulation for pesticide and/or nutrient emissions.
- Banning of certain agricultural inputs (e.g. pesticides).
- Land use regulations.

Instruments focused on the farmer:

- Management support through an extension service.
- Technological support that enables farms to a better access to production technologies.
- Economic support enabling farmers to obtain credits or crop insurance.
- Land tenure.

Agricultural policies, typically, are composed out of one or more policy instruments. Regional land use studies should be able to indicate the (possible) changes that one or a combination of policies will induce. Besides the possible consequences of agricultural policies, stakeholders have to look for policies that are socially acceptable and economically viable. Regulatory instruments, for example, are only successful if they can be enforced. They may therefore not be a feasible solution in many developing countries.

2.4. Technological changes

Changes in agricultural land use can be induced through agricultural policies as illustrated above. They can also be the result of technological changes. Technological changes can be the result of scientific research and successful extension, but also stimulated by agricultural policies and innovative farmers. Technological changes can be sub-divided into:

- Introduction of new crops/animals. The new species/varieties can originate from other regions but also from successful breeding programmes.
- Introduction of new inputs and/or formulation. Agriculture and animal husbandry is increasingly dependent on agricultural inputs to control pests and diseases, to replenish nutrients, and for traction. The introduction of cheaper, more environmentally friendly, more effective inputs may be necessary to fulfil the criteria imposed on the agricultural sector.
- Management changes. Management changes that are frequently being discussed in scientific and more popular publications are those related to integrated pest management (IPM) and integrated nutrient management. They may coincide with the introduction of new inputs and aim at a more 'judicious' manipulation of nutrient stocks and flows, in order to arrive at a 'satisfactory' and 'sustainable' level of agricultural production. In many cases, management changes will change the resource use efficiencies.

2.5. Tools for regional land use analysis

For the development of methodologies for regional land use analysis we have a large number of tools available that can be used to reach our objectives. We distinguish between methodologies and tools. For a specific objective we may need a methodology that comprises a number of tools. Tools for regional land use analysis include programming models, statistical models, and simulation models, but also tools for data management (database management systems, geographical information systems), bio-physical models to estimate crop production and solute flows, and tools for the estimation of input and out parameters of cropping systems. Methodologies comprise a number of these tools that are linked in a specific way to serve the objective of the study.

3. The process of development and implementation

Methodologies for regional land use analysis are often developed and implemented simultaneously. It is a logical result of the structure of the research community. Few donors are interested in methodology development without implementation and the relatively short duration of the projects does not allow for a phased approach with a development phase and an implementation phase. Ideally, we could derive a more generic methodology from a combined development–implementation project.

3.1. General structure

Regional land analysis can only be carried out through intensive multi-disciplinary research. Crissman et al. (1998) defined an organizing principal and conceptual framework for the design and organization of multi-disciplinary research projects. Although they focused on the quantification and assessment of competing objectives in agricultural production systems in terms of trade-offs, the principles seem to have more general validity. This process is illustrated in Fig. 2 and comprises three major steps:

1. *Priority setting*. At the start of a project a joint effort by researchers and stakeholders is required to set research priorities. Within this priority setting it is important that researchers become aware of the opportunity space, the current trends and possible changes induced by agricultural policy. This has to be done in extensive brainstorming sessions and a review of past studies. The major objectives of the study in combination with available resources (including existing data) will determine the focus of research.
2. *Project design and implementation*. This step includes the selection of the relevant disciplines to quantify the processes that are considered to be of major

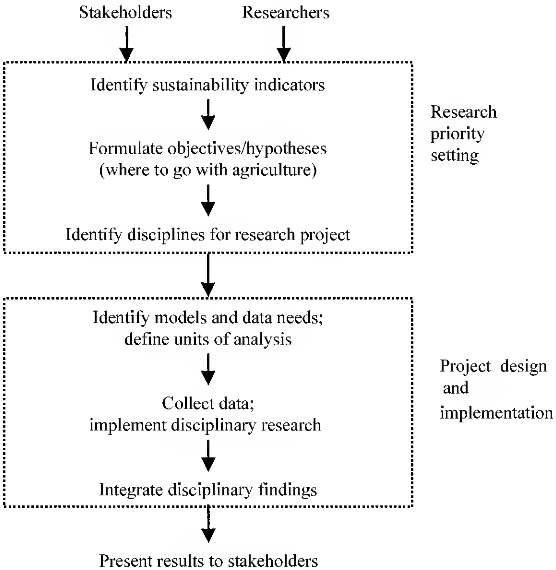

Fig. 2. A structure for the implementation of regional land use analysis. (Source: Crissman et al., 1998).

importance in the first step. It will also include the selection of the appropriate tools. Before the models can be implemented data need to be gathered. In most cases, data gathering is probably the most limiting factor. Policies need to be planned at short notice, leaving little time for extensive data collection efforts. Finally, special efforts are necessary to integrate disciplinary findings.
3. *Presentation of results to stakeholders.* The results need to be presented in such a way that they are understandable and appealing to the stakeholders. Specific concepts like trade-off curves (Antle et al., 1998) may be especially useful since they link up easily with the way policy makers are thinking. New developments in Information and Communication Technology (ICT) can be used to transfer the results to the relevant stakeholders.

Although the scheme seems a rather linear and static approach to regional land use analysis, its strength can be found in a flexible application with numerous feed back loops. Key elements of the scheme include stakeholder involvement at an early stage of the research, the identification of quantifiable indicators for sustainability (but especially the selection of a limited number of indicators) representing the objectives of the stakeholders, and finally, the communication of the research findings in a simple and straightforward manner to policy makers.

What does the scheme imply for a project developing and implementing a methodology for regional land use analysis? The strong involvement of stakeholders in an early stage of the process implies a strong focus on the implementation of the methodology. As a result, it is likely that the methodologies are rather specific and not very generic. Looking at methodologies as a set of combined research tools, one can question what is needed to make them more generic. Specific attention to the units of analysis, uniform database structures, and model structures is essential.

3.2. Units of analysis

Methodologies for regional land use analysis encompass a range of disciplinary tools and databases. Disciplinary research typically operates in a format dictated by disciplinary orientation and generates data intended to satisfy disciplinary objectives. This disciplinary orientation of research leads to a situation in which various pieces of the scientific puzzle are investigated without regard to the fitting together of those pieces into the larger picture that is required for policy analysis. The larger the spatial or temporal scale, the more complex becomes the process of exploring and predicting agricultural land use. Analysis at the regional or national scale is even more difficult than analysis at smaller scales, such as a watershed. Communication between disciplines is only possible if there are clear agreements upon the basic spatial and temporal units of analysis. Typically, regional land use studies work at different hierarchical levels. A larger number of processes take place at large scales (crop growth, pesticide leaching) while others are implemented at small scales (agricultural policies). At the same time, the answers of the analysis are required at a small scale.

The processes need to be studied at the corresponding scale level. As a result, different components of the analysis use different units of analysis and procedures need

to be defined to link the different analyses. We strongly argue for procedures to link the different scales of analysis instead of promoting one single scale level and a single definition for the units of analysis for all disciplinary research. However, this implies that all researchers must address the aggregation problem, i.e. the problem of combining heterogeneous small units into larger units at which agricultural policies are implemented. While much emphasis has been placed on the problem of spatial aggregation, similar problems arise in the time dimension.

3.3. Data standards

Data standards are the key elements for the success of methodologies for regional land use analysis. Only with appropriate data standards the various tools are able to communicate. The data standards applied in the Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al., 1998) are an excellent example to illustrate the importance of data standards. However, DSSAT focuses on crop growth simulation models and the data are limited to the bio-physical environment and crop management.

If data standards are not available, data needs to be 'translated' before tools can communicate. The translation programs make the linkages of tools a rather cumbersome undertaking. Regional land use analysis requires data standards for a large number of disciplinary data sets and they have to be scale independent. As a result, the requisites are much more demanding. The initial investment may, however, pay off at a later stage when it becomes relatively easy to link the different tools. Numerous efforts have been done in the past to standardize soil and climatic data. However, little has been done for the storage of socio-economic data.

Each discipline that is involved in regional land use analysis needs to identify:

- a set of key variables;
- basic units of analysis; and
- structures for database files (including files for both model input as well as model output).

3.4. Model structure

Despite the fact that there is a whole array of models for regional land use analysis, there are four major groups: statistical models, econometric models, programming models, and simulation models. It will be extremely difficult to make a generic structure for land use models in general. For each of the groups, however, a structure can be proposed. Programming models applied in, for example, SysNet and SOLUS are similar in that they use an LP-tableau to represent the technologies for alternative production systems, a set of resource constraints, and an objective function (such as maximization of net income in the region). However, SysNet and SOLUS do not consider the actual farm structure like USTED. SysNet and USTED on the other hand do not consider price elasticity. An alternative to representative-farm programming models is the econometric–process simulation model approach

utilized by Crissman et al. (1998). This approach combines an econometric representation of the production technology with site-specific data in a stochastic simulation framework.

3.5. Toolbox

A toolbox for regional land use analysis is not simply a collection of different quantitative tools. These tools must be adapted so that they can communicate with each other. This can be done through the definition of data standards (as done for crop growth simulation models by Hunt et al. (1994) but also through software (what we call a user shell) that translates the output from one tool to the input of another, or through a combination of both. The concept of a toolbox only functions if a number of basic criteria are fulfilled. First of all, data standards are required that are used by all the tools in the toolbox. Secondly, procedures are necessary to bridge the gaps between different hierarchical scale levels. Finally, the appropriate tools are necessary to present the results in a format that the stakeholders can understand. If the concept works properly, 'plug and play' technology can be applied. Different tools can be combined without requiring any adaptation to the tools themselves. The output of one tool automatically functions as the input for another.

4. A case study for regional land use analysis

One of the questions in policy analysis is what will be the impact of certain agricultural policies. First of all, we have to define a way of presenting these impacts to the stakeholders.

4.1. Trade-offs

In some studies researchers attempt to value environmental effects in monetary terms. Monetary valuation is controversial and fraught with methodological problems. An alternative approach is to quantify trade-offs among different sustainability indicators, present this information to decision makers, and let the decision makers impose their own value judgements. This approach also has the advantage of not obscuring outcomes through the valuation and aggregation process. Trade-off curves show the opportunity cost of what must be given up in one dimension to obtain more in another dimension, for example, what we give up in terms of environmental quality in order to increase agricultural production or income. The concept of trade-offs between present and future outcomes of an agricultural production system can be used to quantify the concept of sustainability and provide quantitative measures of the sustainability of an agricultural production system.

Fig. 3 presents trade-off curves between different outcomes of a production system that illustrate how trade-offs can be used to quantify sustainability. In Fig. 3A, B, the trade-off curves show a positive correlation between agricultural production on the horizontal axis and pesticide leaching and tillage erosion on the vertical axis.

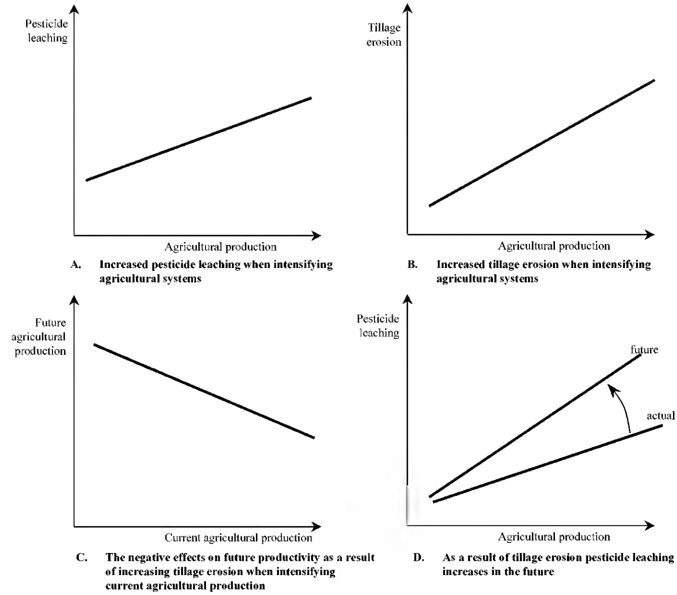

Fig. 3. Examples of trade-off curves.

They indicate that if we increase agricultural production through, for example, higher prices for agricultural products, this will coincide with an increase in pesticide leaching and tillage erosion. Fig. 3C shows the trade-off curve between current and future agricultural productivity. An increase in current agricultural productivity will result in an increase in tillage erosion (Fig. 3B), resulting in a decrease of future productivity. When the outcomes on both axes have a positive social value, the degree of sustainability of a system can be defined as the inverse of the absolute elasticity of the trade-off curve between present and future outcomes (Antle and Stoorvogel, 2001). Thus, a steeply sloped curve in Fig. 3C represents a relatively low degree of sustainability, meaning that for a given production technology and resource endowment, any changes that induce higher levels of current production lead to a rapid reduction in future production potential. Similarly, a relatively flat trade-off curve represents a system with a relatively high degree of sustainability, as increases in current production have relatively little impact on future production potential. Fig. 3D shows that the trade-off curves are not static in time and that the different indicators are not independent. Tillage erosion will lead to topsoil removal and thus a decrease in the capacity of the soil to fix pesticides and prevent them from

being leached to deeper soil layers and ground water. Increasing current productivity will lead to more tillage erosion and the slope of the trade-off curve will increase.

We utilize a static concept of trade-off curves. These trade-off curves provide a method for summarizing the trade-offs among the objectives of interest. In economic terms, the trade-off curves provide essential information for making choices among policy alternatives because they show how much of one desired outcome, such as agricultural production, must be given up to obtain a unit of some other desired outcome, such as improvements in environmental quality of human health.

The trade-off curve is a concrete visualization of the instinctive mental calculations of politicians and other public decision makers. Except in those rare cases of win-win, policy decisions almost always benefit some group at the cost of another group. As widely recognized in the political economy literature (Krueger, 1992), politicians weigh the consequences of their decisions in terms of the costs to the losers and the benefits to the winners. As sustainable agriculture criteria are increasingly incorporated into public decision making, the factors being considered are becoming less comparable. Comparisons are often no longer simply within a single sector but increasingly cross sectors.

A graphical presentation of a trade-off in two-dimensional space such as in Fig. 3 shows the level of agricultural production that can be reached for a given level of environmental impact. The curve shows that as agricultural production increases, adverse environmental impacts also increase. The key features of the trade-off curve are its *location* in the quadrant and its *slope* at a point along it.

The slope of the trade-off curve shows the opportunity cost of increasing agricultural production in terms of foregone environmental quality. This information is critical for informed policy decision making, as it allows policy makers and the public to assess whether a given improvement in environmental quality is worth the sacrifice in agricultural production or income. Note that the relationship is not necessarily linear; at a certain point more and more of one objective must be sacrificed to reach the desired level of the other. Since the objectives that appear on the axes are those determined as important during the research process, these objectives are de facto sustainability indicators of the system of interest.

The particular location on a curve is determined by economic and biophysical factors. Relative prices of agricultural production inputs and outputs determine production through changes in both land use and management intensity. Increasing output prices or reducing input prices induces farmers to allocate more land to the higher priced, more profitable crops, and also encourages them to apply more inputs to those crops. A reduction in output prices or increase in input prices has the opposite effect. In trade-off analysis, trade-off curves are constructed by simulating the response of farmers to various combinations of input and output prices. Each set of prices corresponds to a 'trade-off point' on the trade-off curve.

4.2. Structure of the trade-off analysis

The general structure of the trade-off analysis process is presented in Fig. 4. To quantify in a proper way the sustainability indicators on the axes we have to deal

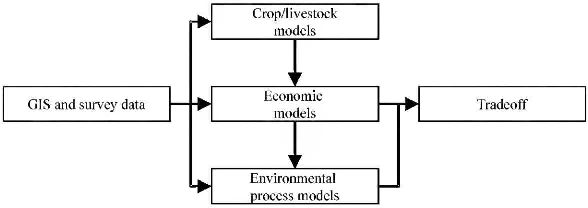

Fig. 4. Structure of the trade-off analysis framework.

the spatial variability in environmental characteristics. As a result, trade-off analysis requires GIS data on the spatial characteristics of land units and survey data. At the same time we need survey data that describe the land allocation and land management decisions of the population of farmers. An economic simulation model is being used to simulate this process as a result of changes in prices and technologies as a result of agricultural policies. An important element that governs the famers' decision-making process is the inherent productivity of the fields. Crop and livestock models are used to simulate the productivity potential of farmers' fields. Subsequently, the economic models are used to simulate the land allocation and land management decisions of farmers. Given simulated land management and the original resource database, environmental models can simulate the environmental impact of these decisions. Finally the results, i.e. the joint distribution of productivity and environmental indicators is represented in a trade-off diagram.

4.3. Spatial scale

In the case of agricultural production we deal with the farmers that finally take the decisions on land allocation and land management. Agricultural policy and markets form the boundary conditions at which the farmers take the decisions.

A diagram, introduced in a soil science context by Hoosbeek and Bryant (1992), is useful to illustrate the research procedure followed in the trade-off analysis (Fig. 4). They utilize two perpendicular axes to represent combinations or research procedures. One represents the range from qualitative to quantitative procedures and the other from empirical to mechanistic. The vertical axis represents a scale hierarchy, where the plot level (the individual soil) occupies the central position (i level). Higher levels are indicated as i+, while lower levels are i−. The scale in Fig. 5 ranges from molecular interaction (i−4) to the world level (i+6).

Different research approaches can be described with this construct of research procedures and placed within the plane obtained at each scale level (Bouma, 1998):

K1: Application of user expertise (qualitative, empirical);
K2: Expert knowledge (qualitative, mechanistic);

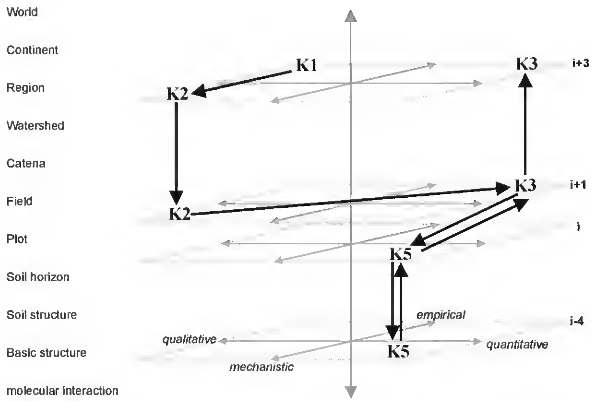

Fig. 5. An illustration of a research chain representing the sequence of research activities at different scale hierarchies for the trade-off model.

K3: Use of simple comprehensive methods, including modelling (quantitative, empirical);
K4: Complex, mechanistic methods, including modelling (quantitative, mechanistic);
K5: Detailed methods, including modelling, which focus one single aspect, often with a disciplinary character (quantitative, mechanistic).

Within the trade-off methodology, we work on different scale levels and use different research approaches. The lines in Fig. 5 represent the so-called 'research chain' that corresponds to the Trade-off model. The Trade-off model demonstrates how the problem is analyzed using different research procedures at different scales. After a very general problem definition by the policy maker (**K1**), the problem is analyzed using expert knowledge (**K2**) as a number of more specific research questions. For example, what will be the effect of an alternative technology on the trade-off between development and pesticide leaching? Since decisions are taken at the farm/field level, the problem is re-defined (still in rather qualitative terms) at the field level: how will pesticide use be affected by an increase in economic performance of the cropping system? In a next step, a quantitative, empirical economic simulation model (**K3**) is used to simulate decision making for different fields. Given the fact that decision making depends on the inherent productivity of that field, crop and/or animal productivity is simulated for one or more points within a field and represented as the inherent productivity of that field. After the simulation of land allocation and land management, environmental processes, like pesticide leaching, can be modeled for a specific point within a field. For both the crop production and

environmental processes quantitative, mechanistic models (**K5**) are used. During the simulation of these bio-physical processes it is necessary to consider processes of nutrient uptake by roots, mineralization of organic matter, and adsorption/desorption of pesticides, processes that occur at the plot and molecular interaction scales. The quantitative results are aggregated to the field level and finally the results of the simulation for many fields are aggregated to the regional scale in the form of trade-off curves (**K3**).

Fig. 5 showed that the trade-off model works at four different scale levels: the regional level (i+4), the field level (i+1), the plot level (i), and lower levels for components of the biophysical models (i−4). Scenarios and boundary conditions are defined at the regional level. The final results of the trade-off analysis will also have to be presented at this level. Land allocation and land management decisions are taken at the field level. Hence, simulation of these decisions takes place at the field level. The crop models and most environmental process models work at the plot level. It is crucial that the different components of the trade-off model can communicate. This means that data will have to be disaggregated (i.e. to move down in the scale hierarchy) or aggregated (i.e. to move up in the scale hierarchy). The disaggregation of data takes place in two different ways mostly depending on the type of data and the way data have been collected.

In the case of soil data, in the existing case study sites an exploratory soil survey is available covering the whole study area. Typically one would use this soil survey, describe representative soil profiles for the different mapping units, and use those profiles for subsequent analyses. However, this would imply that any soil variability within the mapping units is discarded. Since this variability is considered to be large in the Andean highlands, alternative procedures have been developed. The exploratory soil survey is disaggregated using detailed information available from a digital elevation model. Relation between soil variability and parameters describing the topography of the terrain (derived from a digital elevation model) are used. This procedure requires additional field observations but provides the detailed information that is necessary.

Again, in the case study sites detailed economic information exists. The data originate from a dynamic survey of farmer's fields. A representative sample of the fields in the study area was surveyed during a 2-year period. Although the sample was relatively large it does not provide a spatial coverage of the region. The sample does allow for the calculation of distributions of selected economic parameters at the regional level. Instead of disaggregating the information, stochastic procedures are used and parameters are drawn from the distribution. Since the data are based on stochastic procedures fields can be simulated several times with different results.

4.4. Temporal scale

In temporal view, we may follow a classification proposed by Bouma (1997), subdividing management decisions in strategic, tactical and operational decisions. Strategic decisions have a time-scope of 10 years or more and concern issues like the selection of a farming system, such as mixed, organic or integrated farming. The

choice to switch from conventional to precision farming may be considered a strategic decision as well. Tactical decisions cover a period of around 5 years, corresponding roughly to the time-span of a crop rotation. The selection of a rotation scheme involves mainly agronomic considerations. With respect to soils, we may consider soil tillage methods and the required equipment. For instance, minimum tillage or shallow ploughing calls for specific equipment, which can only be successfully implemented when soil properties are taken into consideration. Finally, operational decisions are taken on a day by day basis. These include the selection and timing of management operations, such as planting, harvesting, fertilizer application and crop protection measures.

Depending on the type of policy and the possible effect, we may decide to focus on specific management decisions. The implications for the model choice may be significant. A more static model can deal with strategic and tactical decisions, focusing on crop choice and total inputs and outputs. However, if we deal with operational decisions it will be necessary to use a dynamic model approach, simulating the day to day decisions.

4.5. Linking site-specific economic and bio-physical models

A problem facing empirical production economics research is how to incorporate effects of soils and climate on productivity into economic production models. Production economists have long specified production functions in the general form $q_i = f(v_i, z_i, e_i)$, where q_i is output on the ith field, $\mathbf{v}_i$ is a vector of variable inputs (fertilizer, labour, etc.), $\mathbf{z}_i$ is a vector of fixed capital, and $\mathbf{e}_i$ is a vector of land characteristics including variables representing soils and climate. In practice, the bio-physical factors $\mathbf{e}_i$ are typically represented in economic models by using ad hoc indicators of soil quality and climate such as dummy variables for soil types and average rainfall during the growing season. Theoretically, soil and climate conditions define the potential productivity of a location which, combined with a plant type, management practices, and weather conditions, leads to a realized output. This potential or inherent productivity of the soils and climate in a location can be quantified in the predicted yield of a crop growth simulation model, denoted here as $y(e_i)$. Thus, we specify the production process as $q_i = f(v_i, z_i, y(e_i))$. This specification thus embodies the hypothesis that production is weakly separable in $\mathbf{e}_i$. This is a testable hypothesis.

The crop and livestock simulation models are used to estimate the inherent productivity of each land unit represented in the data. Being a yield estimate, an inherent productivity variable can be multiplied times area in production (or number of animals in the case of livestock production) to obtain an estimate of potential total production on that land unit (or for the given animal herd). This variable is then incorporated into the various econometric models giving each model a spatially explicit productivity characteristics based on bio-physical factors filtered through crop growth models. This information can be interpreted as representing the information the farmer knows about the potential productivity of the land unit when land use and management decisions are being made.

5. Discussion and conclusions

The case study illustrates the complexity of regional land use analysis. All the methods have pro and cons and are based on different techniques. The variety in tools is a logical consequence of differences in questions that need to be answered and the boundary conditions that are set during the development of the methods. The development of operational tools is therefore not restricted to the development of a single methodology. Each of the different methodologies can be less specific to the situation and developed in a more generic way. This facilitates the application in other studies. Only if this last, crucial, but difficult task is accomplished, can we actually say that tools for regional land use analysis are available for specific applications. Currently, few operational methodologies are available for regional land use analysis. Most methodologies are very specific for the specific conditions in which they have been developed. Methodologies for regional land use analysis can only become operational if a number of aspects are kept in mind:

- Stakeholders play a key role in the formulation of research. They are the future users of the results and need to be consulted in an early stage of the project. Ideally they are the actual initiators of the project.
- The analysis of regional land use requires a multi-disciplinary research effort. A more holistic view in disciplinary research is required to enable the linkages. Disciplinary research to study specific components of the system will always play a key role in regional land use analysis.
- Data limitations are often a heavy burden on regional projects. During the development of methodologies, minimum data sets need to be defined that allow users to easily identify the necessary data collection.
- Develop a toolbox for regional land use analysis. For the toolbox to become effective, 'plug and play' technology needs to be developed. This includes data standards for both bio-physical and socio-economic data but also requires the development of more generic tools.

Acknowledgements

The research of Dr. Stoorvogel is funded by the Netherlands Academy of Arts and Sciences. The research of Dr. Antle is funded by the US Agency for International Development.

References

Antle, J.M., Capalbo, S.M., Crissman, C.C., 1998. Tradeoffs in policy analysis: conceptual foundations and disciplinary integration. In: Crissman, C.C., Antle, J.M., Capalbo, S.M. (Eds.), Economic, Environmental, and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 21–40.

Antle, J.M., Stoorvogel, J.J., 2001. Integrating site-specific biophysical and economic models to assess impacts of policy and technology on sustainable land use and soil quality. In: Heerink, N., Van Keulen, H., Kuiper, M. (Eds.), Economic Policy Reforms and Sustainable Land Use. Physica-Verlag, Heidelberg, pp. 169–184.

Bouma, J., 1997. Precision agriculture: introduction to the spatial and temporal variability of environmental quality. In: Lake, J.V., Bock, G.R., Goode, J.A. (Eds.), Precision Agriculture: Spatial and Temporal Variability of Environmental Quality. CIBA Foundation Symposium 210. John Wiley, Chichester, UK, pp. 5–17.

Bouma, J., 1998. Introduction. In: Stoorvogel, J.J., Bouma, J., Bowen, W.T. (Eds.), Information Technology as a Tool to Assess Land Use Options in Space and Time. Proceedings of an International Workshop Lima, 28 September–4 October 1997. Quantitative Approaches in Systems Analysis No. 16. The C.T. de Wit Graduate School for Production Ecology and DLO Research Institute for Agrobiology and Soil Fertility, Wageningen, The Netherlands, pp. 1–11.

Bouman, B.A.M., Jansen, H.G.P., Schipper, R.A., Nieuwenhuyse, A., Hengsdijk, H., Bouma, J., 1999. A framework for integrated biophysical and economic land use analysis at different scales. Agriculture, Ecosystems and Environment 75, 55–73.

Crissman, C.C., Antle, J.M., Capalbo, S.M. (Eds.), 1998. Economic, Environmental, and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production. Kluwer Academic Publishers, Dordrecht, The Netherlands.

De Koning, G.H.J., Verburg, P.H., Veldkamp, A., Fresco, L.O., 1999. Multi-scale modelling of land use change dynamics in Ecuador. Agricultural Systems 61, 77–93.

Hoanh, C.T., Roetter, R.P., Jansen, D.M., Aggarwal, P.K., Lansigan, F.P., Lai, N.X., Bakar, A.A., Tawang, A., 1998. Generalizing SysNet methodologies for land use planning at the sub-national level. In: Roetter, R.P., Hoanh, C.T., Luat, N.V., Van Ittersum, M.K., Van Laar, H.H. (Eds.), Exchange of Methodologies in Land Use Planning. SysNet Research Paper Series No. I. IRRI, Los Baños, Philippines, pp. 41–56.

Hoosbeek, M.R., Bryant, R., 1992. Towards quantitative modeling of pedogenesis — a review. Geoderma 55, 183–210.

Hunt, L.A., Jones, J.W., Hoogenboom, G., Godwin, D.C., Singh, U., Pickering, N., Thornton, P.K., Boote, K.J., Ritchie, J.T., 1994. General input and output files structures for crop simulation models. In: Uhlir, P.F., Carter, G.C. (Eds.), Crop Modeling and Related Environmental Data: A Focus on Applications for Arid and Semiarid Regions in Developing Countries. CODATA, Paris, France, pp. 35–73.

Jones, J.W., Tsuji, G.Y., Hoogenboom, G., Hunt, L.A., Thornton, P.K., Wilkens, P.W., Imamura, D.T., Bowen, W.T., Singh, U., 1998. Decision support system for agrotechnology transfer: DSSAT v3. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 157–177.

Krueger, A.O., 1992. The Political Economy of Agricultural Pricing Policy: A Synthesis of the Political Economy in Developing Countries, Vol. 5. Johns Hopkins University Press, Baltimore.

Lemon, M., 1999. Exploring Environmental Change Using an Integrative Method. Gordon and Breach Science Publishers, Amsterdam.

Ritchie, J.T., 1995. International consortium for agricultural systems applications (ICASA): establishment and purpose. Agricultural Systems 49, 329–335.

Van Ittersum, M.K., Rabbinge, R., Van Latesteijn, H.C., 1998. Exploratory land use studies and their role in strategic policy making. Agricultural Systems 58, 309–330.

Van Keulen, H., Kuyvenhoven, A., Ruben, R., 1998. Sustainable land use and food security in developing countries: DLV's approach to policy support. Agricultural Systems 58, 285–307.

Wiebe, K.D., Meinzen-Dick, R., 1998. Property rights as policy tools for sustainable development. Land Use Policy 15, 203–215.